



# **THE ROLE OF THERBLIGS IN AUTOMATED DESIGN PROCESS MAPPING**

**R.C.W.SUNG, J.M.RITCHIE, G.ROBINSON, P.DAY, J.R.CORNEY AND  
H.J.REA**

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## ABSTRACT

*The research presented in this paper involves the detailed analysis of a user's actions whilst carrying out a design activity in a virtual reality (VR) environment. It is proposed that the analysis can be used to extract the design knowledge that is generated during the design session. By parsing and analysing the log files, motion study analysis and process planning can be performed automatically. Furthermore, IDEF0 diagrams can be automatically generated which allow the processes occurring during the design session to be easily described and visualised. The outcome of all the analysis will benefit future users by aiding them in creating more efficient designs that will contain fewer errors and be less time-consuming to produce.*

## 1. INTRODUCTION

When a designer completes a design in a computer-aided design (CAD) environment, the end result contains only the solution to the design problem, but none of the design knowledge that is created, or learned, during the session. This means that the reasons the designer came up with the final solution will not be known to other users, unless that information was explicitly stated by the designer, either during the design session or afterwards. However, having to record this extra information will not only take more time and effort, but it will also disrupt the design process and creativity of the user. Therefore, it is proposed that if each individual action of the user during the design session could be logged and analysed, it would give the potential for formalising the design rationale of the designer. Rationale, in this case, refers to the user's reasons for making their design decisions during the session. Since the logging is carried out unobtrusively and automatically in the background, the designer will not be disrupted and no extra work will be required from them to record their design actions. After obtaining the formalised design rationale, it could then be used to aid subsequent users, who are carrying out a similar design task, by providing hints to them as well as identifying any mistakes that they have made. In the research presented in this paper, the actions of a user are logged while they are designing a cable assembly in a virtual design environment, and then various techniques that are applied to analyse the logged data is detailed.

The paper starts by discussing the related research in user-logging and cable design, and then the immersive VR apparatus and experimental methodology used in this research is detailed. This is followed by a section demonstrating the potential for automatically generating manufacturing planning data. Furthermore, several visual techniques for representing the user activity from the log files are presented which aid the identification of signature patterns relating to design rationale. Next, the benefits of representing the design processes using IDEF diagrams, and a way to generate them automatically, is presented, before finally drawing some conclusions.

### ***1.1 User Logging and Design Intent Identification***

By considering the thoughts of the designer, it is possible to identify how important the cognitive issues associated with design, as a creative process, are. In McPhee [1], design is described as a mysterious mix of science and art that can only be understood by first understanding how humans think and behave. It is also mentioned that design is

instinctive, as does Schöns's "knowing-in-action" theory [2]. Where instinctive activity does not lead to a satisfactory outcome, the designer suffers a "breakdown"; a difficulty that makes tacit reasoning more explicit [3]. Studies also repeatedly show individual's design approaches as unsystematic and ad hoc despite the influence of an explicit rationalistic guiding procedure [4]. Even when using the same methods designers produce appreciably different designs [5] and their behaviour may be as a consequence their cognitive load [6]; thus, the related notion of "modal shifts" also emerges [7]. Immersive VR of the kind used in this research provides the potential for the non-intrusive analysis of design tasks and the recognition of associated patterns of behaviour in a number of contexts which would be difficult with CAD. This is further amplified in downstream manufacturing planning task extraction.

The capability of VR for design tasks was demonstrated by COVIRDS (COncceptual VIRTUAL Design System) which showed the interactive capabilities of immersive virtual design [8]. Varga *et al.* [9] have also investigated the use of hand motion as a means of creating conceptualised geometry for design purposes and suggest a novel classification scheme for categorising these motions. Holt *et al.* [10] also showed that immersive VR has an important role to play in the design process.

There has also been research in exploiting the user-logging data created during a VR session to enhance the design process or to aid in identifying design intent. Research by Ritchie *et al.* [11] has investigated the use of data in log files to automate the process of generating assembly plans. Wyatt *et al.* [12] analysed the log files from a VR geotechnical laboratory to help create a more interactive design tool which will guide users whilst they are carrying out experiments. The research carried out by Brough *et al.* [13] involves logging users whilst they are being trained to carry out assembly tasks in a VR environment. The logged data is then utilised to generate 'hints' that can be presented to the user to give guidance, if required. Finally in Greenhalgh [14], users are logged whilst having a VR teleconference to help determine characteristics related to the movement of users and world transition.

Finally, in Dey *et al.* [15], users are logged whilst working an office environment using video cameras, audio recorders, various sensors and also by monitoring their computer usage. By instructing the system of what logged events occur when a particular task is being carried out by the user, it means that when the same events occur in the future, the system will recognise this and a certain action can be programmed to occur automatically.

From the literature presented in this section, it can be seen that there are benefits in using VR technologies to log user actions, but much work has still got to be done in trying to extract the design knowledge that may be stored in the logged data.

## ***1.2 Cable Harness Design Using Virtual Environments***

The designing of cable harnesses, which refers to the assembly of cable, connectors and clips, is a classic design problem and, even with the application of extensive CAD-based packages available, many companies still utilise physical prototypes to create the cable routes and to verify the design [16]. In addition, human expert intervention is still required to make fine adjustments and verify the solutions. Therefore, it would be advantageous to investigate the nature of new human-driven tools to support interaction with data in this domain. According to [17], integrating the human expert into the

'system' is crucial within VR applications because it treats the operator as an integral part of the system. This will also help to alleviate the problem where, sometimes, multiple physical prototypes are required to solve design problems, which will lead to a delay in introducing the cable harness to market [16].

In this domain, VR's unique capability makes it a powerful tool with which to carry out detailed design and manufacturing studies. Furthermore, the task of designing a cable harness is flexible enough to allow some form of limited task variety to be built into system experiments.

Earlier work at Heriot-Watt University [18, 19, 20, 21] in the area of cable harness design compared an immersive VR design environment with a number of CAD systems. The results showed that VR gave productivity benefits over CAD during creative cable routing design activities. Follow-on work was aimed at understanding the degree to which various aspects of the immersive VR system were contributing to these benefits and how engineering design and planning processes could be analysed in detail, automatically, as they are being carried out.

## 2. APPARATUS AND METHODOLOGY

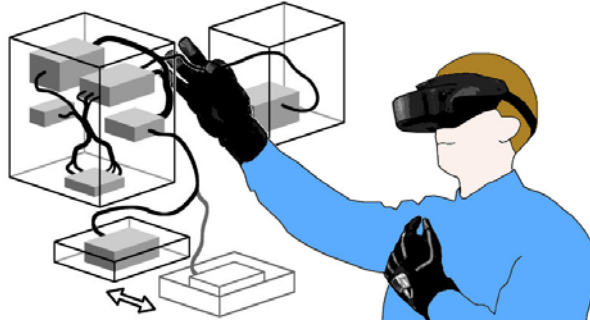
### 2.1 Apparatus

The experimental platform developed for this research was called COSTAR (Cable Organisation System Through Alternative Reality) and was implemented on an SGI® Octane2™ with V12 dual head graphics driving each eye on a V8 stereo head-mounted display (HMD) shown in Figure 1. Peripherals attached to the system were a Flock of Birds® magnetic tracking system and Pinch® Gloves with system software platform being SENSE8®'s WorldToolKit® release 9.



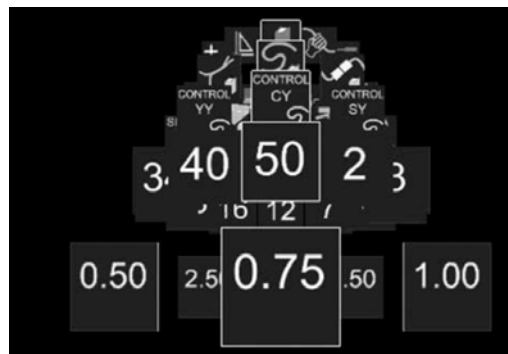
**Figure 1 - Head-mounted display (HMD)**

Using COSTAR the engineer can design and assembly-plan cable harness assemblies within the immersive VR environment with all design functions being performed while immersed in the system as shown, schematically, in Figure 2. Interactions are achieved using a hierarchical ring menu system [8,16], shown in Figure 3, and glove pinch gestures supported by spatial input given by the Flock of Birds™ system.

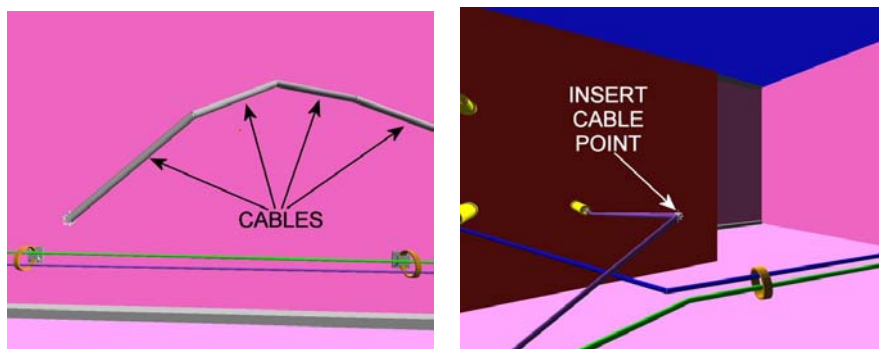


**Figure 2 - The COSTAR cable harness design system**

An engineer inputs cable harness routes by plotting points in 3D space joined together to produce a segmented cable path. Subsequent cable editing is possible by selecting points and bending them around obstructions or bundling them. The user can also insert new points and add connectors and fasteners. Figure 4 shows the system in use.



**Figure 3 - Hierarchical ring menu**



**Figure 4 - Creating a cable from point to point (left) and inserting a cable point (right)**

## 2.2 User Logging

As the user operates the system, the system logs all of the user's cable harness design and assembly activity-related actions. Since the logging occurs unobtrusively in the background, the user is not aware of the logging process, which means the user's design process will not be interrupted.

Figure 5 shows part of the log file which lists each action carried out by the user, whether it's a menu selection or a change in the design, with each record having a timestamp next to it, so all the user's design actions are in chronological order.

```

-----
CO-STAR* prototype virtual design environment
-----

Filename: data:p1101 user actions8 w*
Time: Mon Feb 7 14:13:39 2005

User specific details. IPB:1* arm length:400*
This file contains details of user actions. Lines are of the following form:
Secs.micsecs Gesture Description of event ID of 1st object Name of 1st object Type of 1st object ID of object2 Name of object2
-----
1107785644.93163 Creating Chassis: A01B0
1107785644.93419 Creating Fastener: A01H01F01 Name: FAS01
translated to (2500,-300,3750) and oriented at (-0.5,-0.5,-0.50.5)
1107785644.93661 Creating Fastener: A01H01F02 Name: FAS02
translated to (1250,-300,3750) and oriented at (-0.5,-0.5,-0.50.5)
1107785644.93896 Creating Fastener: A01H01F03 Name: FAS03
translated to (0,-300,3750) and oriented at (-0.5,-0.5,-0.50.5)
1107785644.94112 Creating Fastener: A01H01F04 Name: FAS04
translated to (-1250,-300,3750) and oriented at (-0.5,-0.5,-0.50.5)
1107785644.94408 Creating Fastener: A01H01F05 Name: FAS05
translated to (-2500,-300,3750) and oriented at (-0.5,-0.5,-0.50.5)
1107785644.94624 Creating Fastener: A01H01F06 Name: FAS06
translated to (-3750,-300,1000) and oriented at (0,0,-0.7071070.707107)
1107785644.94893 Creating Fastener: A01H01F07 Name: FAS07
translated to (-3750,-300,1000) and oriented at (0,0,-0.7071070.707107)
1107785644.95112 Creating Fastener: A01H01F08 Name: FAS08
translated to (-3750,-300,-500) and oriented at (0,0,-0.7071070.707107)
1107785644.95328 Creating Fastener: A01H01F09 Name: FAS09
translated to (-7500,-300,-2450) and oriented at (0,0,-0.7071070.707107)
1107785644.95543 Creating Fastener: A01H01F10 Name: FAS10
translated to (-7500,-300,-750) and oriented at (0,0,-0.7071070.707107)
1107785644.95760 Creating Fastener: A01H01F11 Name: FAS11
translated to (-7500,-300,1000) and oriented at (0,0,-0.7071070.707107)
1107785644.96036 Creating BulkheadConnector: A01B01 Name: CON01
1107785644.96231 Creating BulkheadConnector: A01B02 Name: CON02
1107785644.96435 Creating BulkheadConnector: A01B03 Name: CON04
1107785644.96630 Creating BulkheadConnector: A01B04 Name: CON05
1107785644.96820 Creating BulkheadConnector: A01B05 Name: CON07
1107785644.97031 Creating BulkheadConnector: A01B06 Name: CON08
1107785644.97225 Creating BulkheadConnector: A01B07 Name: CON10
1107785644.97484 Creating BulkheadConnector: A01B08 Name: CON11
1107785644.97682 Creating BulkheadConnector: A01B09 Name: CON14
1107785644.97884 Creating BulkheadConnector: A01B10 Name: CON18
1107785644.97932 BulkheadConnector: A01B01 translated to (3250,-500,3725) and oriented at (0,-0,0.7071070.707107)
1107785644.97961 BulkheadConnector: A01B02 translated to (3250,-1000,3725) and oriented at (0,-0,0.7071070.707107)
1107785644.98005 BulkheadConnector: A01B03 translated to (2250,-500,325) and oriented at (-0,-1,-04.37114e-08)
1107785644.98060 BulkheadConnector: A01B04 translated to (1750,-500,325) and oriented at (-0,-1,-04.37114e-08)
1107785644.98106 BulkheadConnector: A01B05 translated to (2250,-1500,325) and oriented at (-0,-1,-04.37114e-08)
1107785644.98151 BulkheadConnector: A01B06 translated to (1750,-1500,325) and oriented at (-0,-1,-04.37114e-08)
1107785644.98196 BulkheadConnector: A01B07 translated to (-2250,-500,-2175) and oriented at (-0,-1,-04.37114e-08)
1107785644.98242 BulkheadConnector: A01B08 translated to (-3000,-500,-2175) and oriented at (-0,-1,-04.37114e-08)
-----
For Help, press F1

```

Figure 5 - User Log File

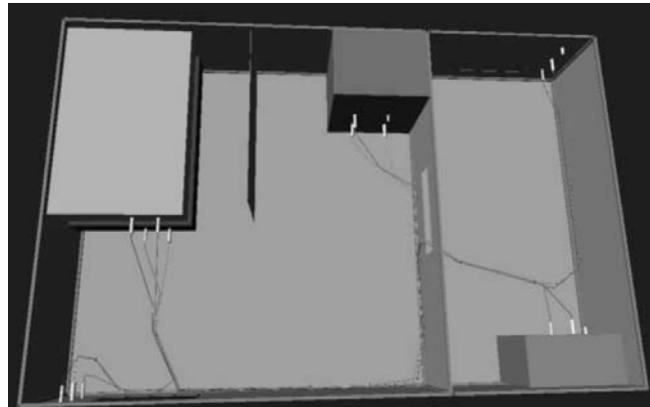
### 3. EXPERIMENTAL PROCEDURE AND ANALYSIS

Three constrained design tasks were developed and implemented to evaluate each designer's time on the system. These covered common harness design activities such as routing, bundling, cable modification and choosing connectors. The log files were subsequently analysed to identify which areas of the virtual design system were used, the type of activity performed and their distribution within the total design time. The participants were given sufficient information about the goals of the task along with the main boundary conditions but were given the freedom to determine the final design solution. This task uncertainty prevented the evaluation process from being a prescriptive controlled experiment which gave the participants the feel of doing a real cable harness design task using a realistic product model (Figure 6) and involved the following tasks:

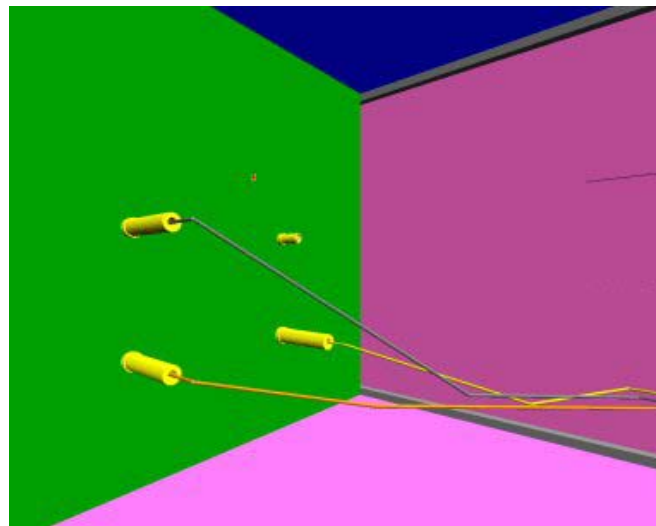
**Task 1: Outline Design** – This task, and the following one, is for training and familiarisation purposes and involves the user generating two new electrical interconnections within the product model using specific connectors and a specified cable type.

**Task 2: Detailed Design** – Using pre-defined cable interconnections in a model, a number of which had already been routed through a sequence of cable clips, the user had to route the outline cables in the model through the cable clips to complete the cable

harness design. Engineering judgement had to be used regarding what the harness design solution was and how it was achieved. Figure 7 shows a partially completed route.



**Figure 6 - Model on completion of the experimental tasks**



**Figure 7 - A partially completed route**

**Task 3: Redesign** – The key experimental design evaluation task, this began with a product model containing a completed, fully designed harness assembly. The user had to complete some ‘engineering change requests’ requiring redesign of the cable harness. The specific changes required were the addition of a new cable and the removal of one of its associated connectors. Finally, there was another ‘undefined’ error within the model – a cable routed through a solid wall – which the participants were required to locate and fix by rerouting.

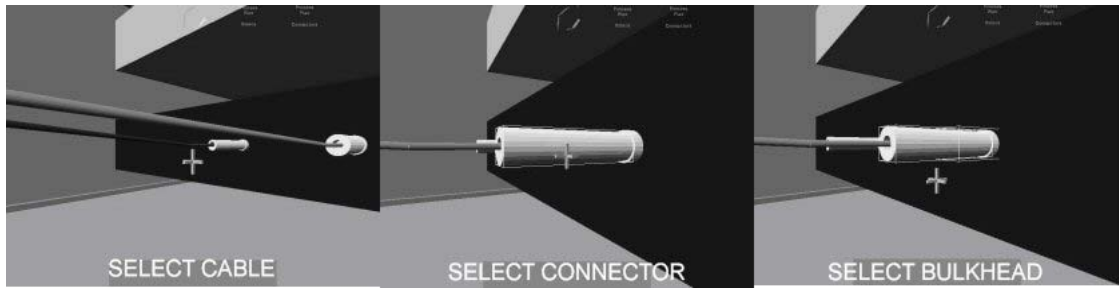
Ten engineers completed the experiments, all of whom were male, eight were 20 – 29 years of age and two were 30 – 39 years of age, all with normal or corrected-to-normal vision. Everyone was right-hand dominant with eight being right eye and two being left-eye dominant. Seven of the participants estimated that they had between 10 – 100 hours of previous CAD experience with three estimating 100–1,000 hours experience. Seven also had no prior VR experience, two had less than 10 hours and one had 100-1,000 hours of VR exposure. The design activity was followed by a semi-structured interview

during which feedback was collected. For detailed statistical analysis of the results, see section 4 of [19].

#### 4. CABLE HARNESS ASSEMBLY AND INSTALLATION PLANNING

In industry, there are still occasions where the assembly plan is still generated, manually, by the designer, which is both time-consuming and can also be disruptive to the creative process. Therefore, it was decided to investigate the possibility of automatically generating assembly plans for assembling and installing a cable harness, whilst using the immersive VR interface.

The process involves the user exploring the equipment assembly (Figure 8) and then: (1) choosing connector positions within the bulkheads to mimic bulkhead connector installation; (2) selecting cable harness and associated connector geometries to demonstrate a cable harness assembly process planning; and (3) indicating the cable and bulkhead connector attachments to emulate the installation of the final cable harness in the virtual model.



**Figure 8 - VR user interface for assembly planning**

While the user is carrying out these tasks, all the actions are non-intrusively logged by the system. From the logged data, the automatic parsing of the associated files and analysis of the data syntax allows the translation of the standard syntax into associated standard-English instructions. This automatically generates an installation assembly plan, presented in Figure 9, from the data which requires no interactive creation of instructions or subsequent amendments from the user.

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**BULKHEAD CONNECTOR INSTALL SEQUENCE**  
 -----

Op Num	W/Centre	Assembly Instructions	Tooling	Assembly Time (s)
10	Cable Bench	Connect bulkhead connector CON01 (Type: plug Shell size: 1 Number of poles: 2) to bulkhead 3250 located at position (3250,-500,3725) and Orientation (0,-0,0.707107,0.707107)	Hand Assembly	7.8
20	Cable Bench	Connect bulkhead connector CON04 (Type: socket Shell size: 1 Number of poles: 2) to bulkhead 2250 located at position (2250,-500,325) and Orientation (-0,-1,-0,4.37114e-08)	Hand Assembly	19.9
30	Cable Bench	Connect bulkhead connector CON05 (Type: socket Shell size: 2 Number of poles: 7) to bulkhead 1750 located at position (1750,-500,325) and Orientation (-0,-1,-0,4.37114e-08)	Hand Assembly	17.7
40	Cable Bench	Connect bulkhead connector CON10 (Type: plug Shell size: 2 Number of poles: 7) to bulkhead -2250 located at position (-2250,-	Hand Assembly	29.6



500,-2175) and Orientation (-0,-1,-0,4.37114e-08)

Figure 9(a)

CABLE HARNESS BUILDING SEQUENCE				
Op Num	W/Centre	Assembly Instructions	Tooling	Assembly Time (s)
10	Cable Bench	Connect cable CAB02(Type: CONTROLCY Number of Cores: 7 Core Cross-Section: 1 Colour (RGB): 225,125,0) to inline connector CON23 (Type: plug Shell size: 2 Number of poles: 7)	Hand Assembly	8.2
20	Cable Bench	and inline connector CON24 (Type: socket Shell size: 2 Number of poles: 7)	Hand Assembly	22.6
30	Cable Bench	Connect cable CAB01 (Type: SINGLECORE Number of Cores: 1 Core Cross-Section: 4.8 Colour (RGB): 255,0,0) to inline connector CON22 (Type: plug Shell size: 1 Number of poles: 2)	Hand Assembly	7.6
40	Cable Bench	and inline connector CON21 (Type: socket Shell size: 1 Number of poles: 2)	Hand Assembly	20.7

Figure 9(b)

INSTALL CABLE HARNESS ASSEMBLY INTO EQUIPMENT				
Op Num	W/Centre	Assembly Instruction	Tooling	Assembly Time (s)
10	Assy Station	Connect inline connector CON21 (Type: socket Shell size: 1 Number of poles: 2) to bulkhead connector CON01 (Type: plug Shell size: 1 Number of poles: 2) located at position (3250,-500,3725) and Orientation (0,-0,0.707107,0.707107)	Hand Assembly	5.7
20	Assy Station	Connect inline connector CON22 (Type: plug Shell size: 1 Number of poles: 2) to bulkhead connector CON04 (Type: socket Shell size: 1 Number of poles: 2) located at position (2250,-500,325) and Orientation (-0,-1,-0,4.37114e-08)	Hand Assembly	14.8
30	Assy Station	Connect inline connector CON23 (Type: plug Shell size: 2 Number of poles: 7) to bulkhead connector CON05 (Type: socket Shell size: 2 Number of poles: 7) located at position (1750,-500,325) and Orientation (-0,-1,-0,4.37114e-08)	Hand Assembly	9.1
40	Assy Station	Connect inline connector CON24 (Type: socket Shell size: 2 Number of poles: 7) to bulkhead connector CON10 (Type: plug Shell size: 2 Number of poles: 7) located at position (-2250,-500,-2175) and Orientation (-0,-1,-0,4.37114e-08)	Hand Assembly	70.7

Figure 9(c)

STANDARD REAL WORLD ASSEMBLY TIMES FOR EACH COMPONENT			
Component	Assembly Time (s)	Component	Assembly Time (s)
CAB01	7.592	CON22	22.36
CAB02	8.233	CON23	17.36
CON01	13.56	CON24	93.27
CON04	34.63	BH-2250	29.63
CON05	26.83	BH1750	17.70
CON10	100.3	BH2250	19.87
CON21	26.40	BH3250	7.844

Figure9(d)

**Figure 9 - Assembly plans generated from assembly planner logging**

This approach supports the work carried out by Ritchie *et al.* [21] which showed that production of usable assembly plans via an immersive VR interface. However, Dewar *et al.* [22] demonstrated that the assembly times obtained in the virtual environment are different from real-world times. To overcome this problem, the COSTAR system can look up a table of standard real-world assembly times, and then map these times onto the corresponding virtual assembly operation. This matching of real world times with their virtual-equivalent activities also demonstrates wider and more profound opportunities, such as how interactive systems of this kind could be used in generic project planning domains by carrying out interactive assembly/disassembly in exactly this way [23] for applications such as project planning as well as demonstrating the potential for outputting structured data, from the subsequent analysis of which could form the basis for formalizing manufacturing intent. All this enables the development and generation of production-readable assembly plans without the need for human intervention, which is not possible with traditional CAD methods. Furthermore, the feasibility of the assembly plans and accessibility issues relating to the harness can be checked ergonomically.

## **5. AUTOMATED LOG FILE ANALYSIS, MOTION STUDY AND PROCESS MODELLING**

### ***5.1 Log File Analysis***

In earlier work, the logged data generated during the VR design sessions were all categorised and analysed, manually, which proved to be very time consuming. Therefore, a spreadsheet macro was written that could carry out the analysis tasks automatically. The first step in the macro is to parse the log file and assign each user action into various categories which will aid in further analysis (Figure 10). Next, a process flow diagram is automatically generated from the categorised log file, which is the first time that this has been possible for a realistic design task.

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p05t03_user_actions_classification - WordPad
File Edit View Insert Format Help
0 Inter-Sequence Break End
0 Information Start - Welcome Screen
0.026444 Information End
0.026444 Inter-Sequence Break Start
6.00112 Inter-Sequence Break End
6.00112 Navigation Start
6.04832 Navigation End
6.04832 Inter-Sequence Break Start
34.6964 Inter-Sequence Break End
34.6964 System Operation Start
43.4457 System Operation End
43.4457 Navigation Start
50.5269 Navigation End
50.5269 System Operation Start
58.5606 System Operation End
58.5606 Design Goal Start deleting cable A01H01C02 CAB02
59.3285 Design Goal End
59.3285 Navigation Start
92.9413 Navigation End
92.9413 System Operation Start
102.307 System Operation End
102.307 Navigation Start
108.673 Navigation End
108.673 System Operation Start
112.273 System Operation End
112.273 Navigation Start
122.64 Navigation End
122.64 Information Start
141.423 Information End
141.423 Navigation Start
142.173 Navigation End
142.173 System Operation Start
159.038 System Operation End
159.038 Information Start
189.189 Information End
189.189 Design Support Start Creating connector A01H01I13
192.306 Design Support End
192.306 Design Goal Start placed inline connector A01H01I13 SOCKET, 8 poles, 2

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**Figure 10 – User Activity Categorisation**

### 5.2 Therbligs

From observing the users, whilst carrying out a design task in the VR environment, it was seen that many of the body motions were similar to those of a person carrying out a real-world assembly process. Therefore, it was decided that it would be beneficial to study the motions performed in the VR environment, so an analysis method was searched for. In the end, the best candidate found was Gilbreth’s *therbligs* [24,25]. *Therbligs*, invented by Frank Gilbreth, consists of a library of symbols that represent all the mental and physical processes that occur during an assembly task; these are summarised in Figure 11.

SEARCH		TRANSPORT EMPTY		PRE-POSITION	
FIND		POSITION		RELEASE LOAD	
SELECT		ASSEMBLE		UNAVOIDABLE DELAY	
GRASP		USE		AVOIDABLE DELAY	
HOLD		DISASSEMBLE		PLAN	
TRANSPORT LOADED		INSPECT		REST	

**Figure 11 - Therblig symbols**

By studying the mental and physical processes that occur for each design task, it was possible to map the *therbligs* onto each user action in the log file. This was then extended by mapping the *therbligs* to the process flow diagram to give a detailed chronological history of the user's activity (Figure 12), which can be studied in more detail.

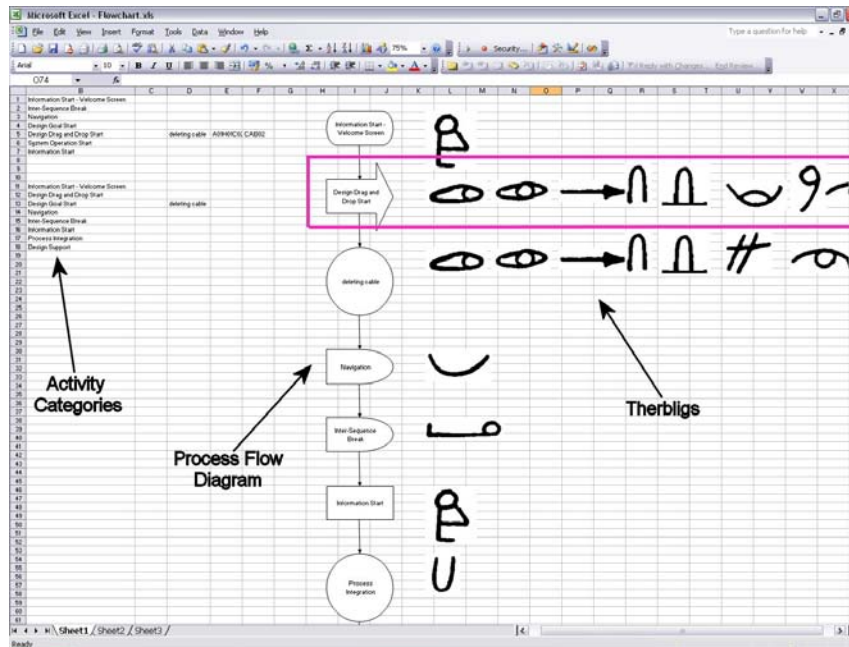


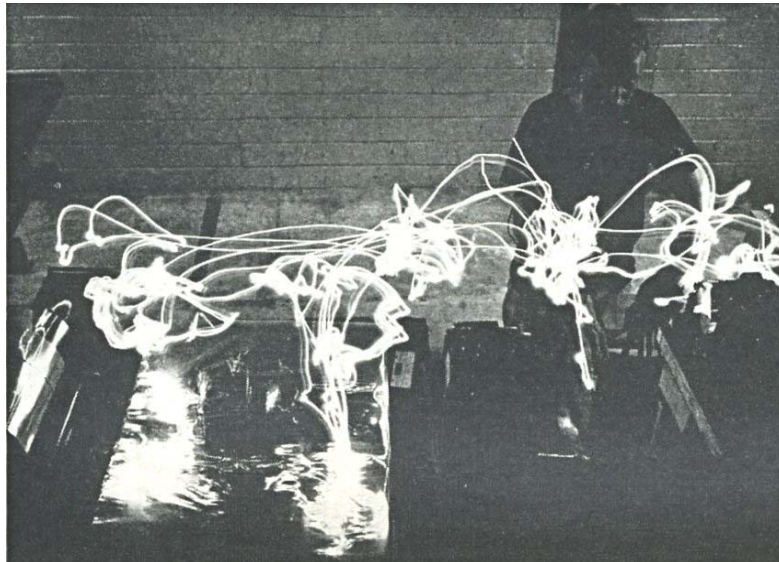
Figure 12 - Process flow diagram and therbligs

For example, in line 2 of the process diagram (highlighted) it can be seen during this part of the 'Design Drag and Drop Start' process, that the user is searching for and then finding the cable to be moved. Next, the cable is selected, grasped, held and then transported to a different location. Finally, the cable is positioned in the correct position and released. Similar *therbligs* can also be generated for other assembly approaches [26].

From the preliminary results, it can be seen that *therbligs* can give a quick visual analysis for identifying inefficiencies in the process, and repeated design behaviour exhibited by the user. The most important benefit of using this analysis method is that it can be carried out automatically and, potentially, in real time.

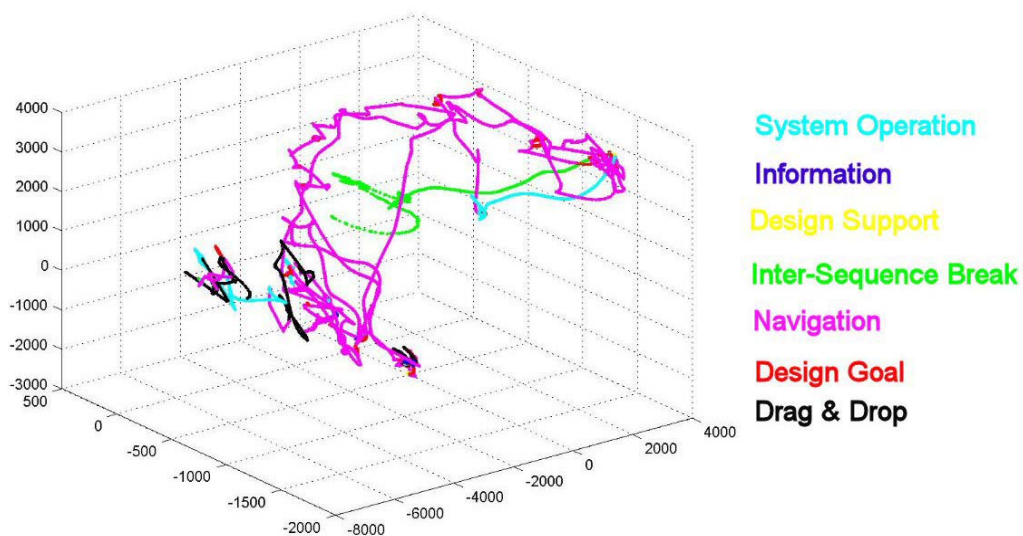
### 5.3 Chronocyclegraphs

Another Gilbreth creation developed to study motion during assembly processes and adopted in this research to investigate design interaction in 3D environments is the use of the *chronocyclegraph* [25]. Traditionally, the technique involved attaching a light source, flashing at a known constant frequency, to the operator's hand while they are carrying out a task. This process is recorded over a period of time using one long-exposure photograph and the resulting photograph shows the continuous path of the person's hand while performing the task (Figure 13). This path is known as the *chronocyclegraph*. From the flashing of the light source, and the positions of the bulbs during exposure, velocities and accelerations can be calculated, if required.



**Figure 13 - Chronocyclegraph**

By viewing the *chronocyclegraph*, regions of unnecessary motion and activity from the user will be identified and, therefore, the design of the VR interface can be optimised by removing any inefficiency. Since the position and orientation of the user's head and hands are tracked and logged during a design session, the tracking data can be used to generate a *chronocyclegraph* automatically, as shown in Figure 14.



**Figure 14 - Left Hand Motion Path**

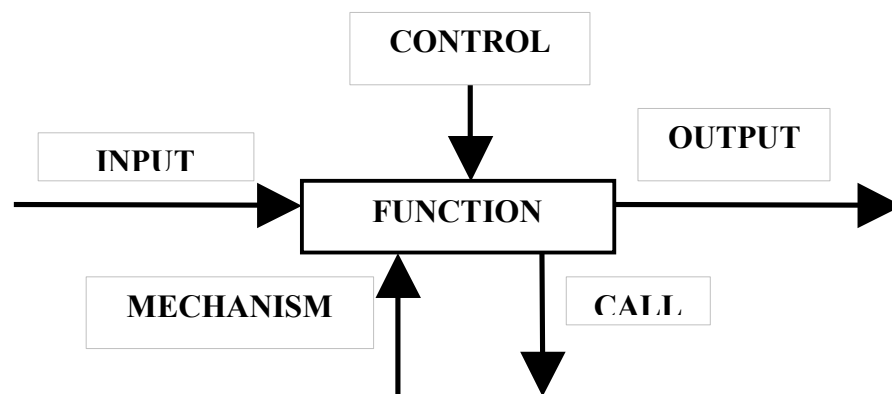
The figure shows the path that the user's left-hand takes during a design session with the colours of the path corresponding to a particular category of activity. Since a timestamp is attached to each user action, the velocity and acceleration of the user's motion can be calculated, in a similar fashion to the original *chronocyclegraphs*. One potential use of the velocity and acceleration information would be to gauge the designer's confidence level based on the speed of movement and level of deviation in the direction of travel. Furthermore, *therbligs* can also be mapped onto positional information linking the detailed design and user interface task analysis classification

with the design categorisation. In addition, this will provide an ability to “replay” a previous design activity and would also allow a design to be “rolled back” to a specific point to let the designer to work on it again.

The work carried out in this research and in [26] is the first time that Gilbreth’s methods have been combined in this way to analyse virtual tasks of this kind.

#### 5.4 IDEF0 Diagrams

During the 1970s, a collection of techniques, called IDEF (Integrated computer-aided manufacturing DEFINitions), was developed to provide various methods to store and study activities that are carried out in manufacturing. One subset of IDEF is IDEF0 which is used to model processes and gives a visual representation of the “functions, activities or processes within the modelled system or subject area.”[27]. This technique has since been widely used as an industry standard to formally view the processes that occur during a design activity.

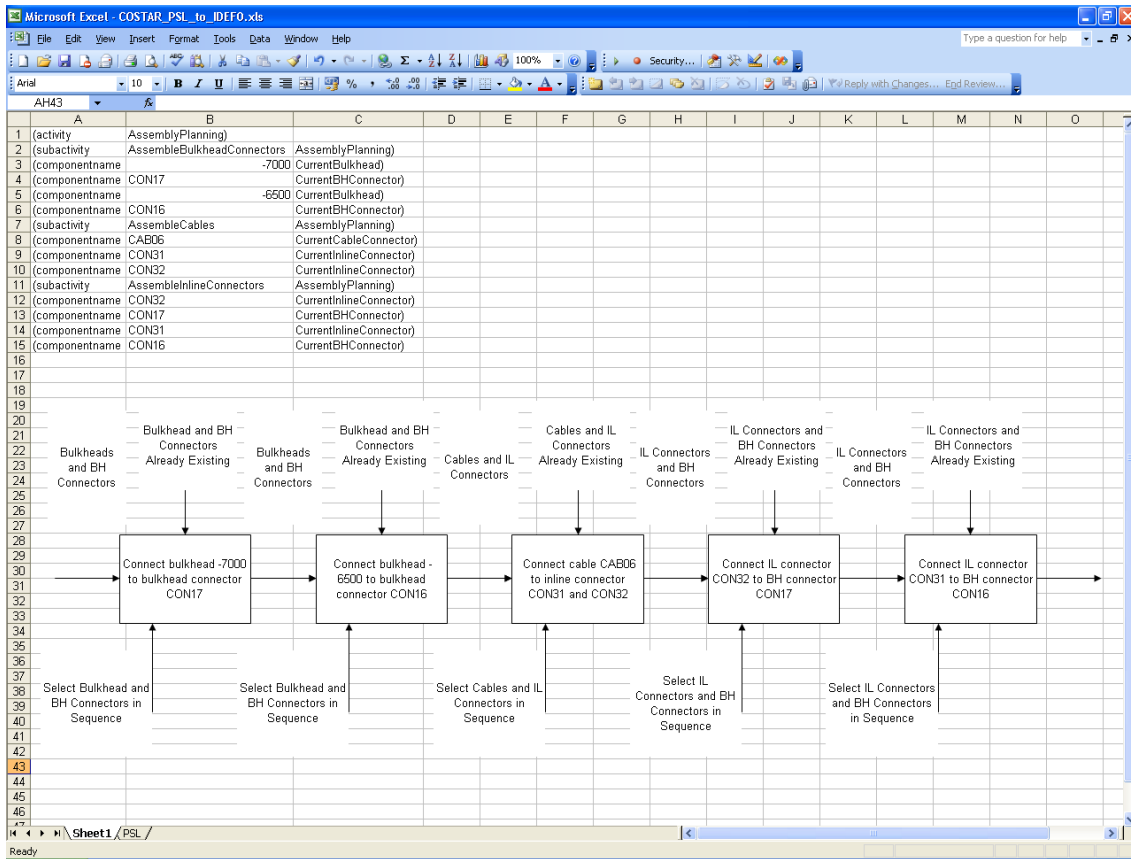


**Figure 15 - IDEF0 Diagram**

Figure 15 shows a generic IDEF0 diagram which is made up of the following elements:

- INPUT: the data, or objects, that are transformed by the function into the output,
- CONTROL: conditions required to produce the correct output,
- MECHANISM: the means used to perform a function,
- OUTPUT: the data, or objects, produced by a function,
- CALL: enables the sharing of details between models or between portions of the same model.

To generate the IDEF0 diagrams, automatically, a spreadsheet macro was created that parses the user activity log file, or a process specification language (PSL) equivalent [28], and identifies specific design activities, such as moving a cable, creating a connector or assembly planning. Then, an IDEF0 diagram to represent this process is generated automatically, as show in Figure 16.



**Figure 16 - Automated Generation of IDEF0 Diagram**

By viewing the IDEF0 diagram, the steps that were carried out by an expert user during a particular design task can be identified, and then be utilised in an online help system by future users who require help when working on the same task. At present, the information contained in the IDEF0 diagrams is only at a basic level but more detailed information will be added in future work.

In the example illustrated in Figure 16, an IDEF0 diagram is used to model the process of generating an assembly plan, but another suitable modelling technique that could be used is IDEF3. This was developed a few years after IDEF0 to describe sequences of events that occur in situations such as manufacturing, and this is the information that is contained in an assembly plan. However, not all actions in the cable harness design system is as suitable to be modelled using IDEF3 because they only consist of a single event, rather than a sequence. Therefore, using a combination of both modelling methods could be a possibility for future research.

## 6. CONCLUSIONS

This paper has presented an automated way to generate assembly plans by utilising the data that is logged from the user during a design activity. To give more realistic assembly operation times, a table of standard real-world assembly times have been mapped onto the corresponding virtual operation.

In addition, two analysis methods, called *therbligs* and *chronocyclegraphs*, have been applied to study a user's motion when carrying out a design task in the virtual



environment, to gain a detailed understanding of the user interactions and process activities. Both methods have allowed any inefficiency in the user's motion, processes and VR interface design to be visually identified and analysed. One potential application of the data obtained from the analysis is the extraction of 'thinking time' by searching for pauses in the user's activity or changes in their behaviour. This may highlight areas where the user is thinking about the design, and may imply design intent, or reasoning, from the actions leading up to, and after, an event where a design decision has been made.

Finally, it is proposed that further analysis of the log files can allow design knowledge to be acquired. Once the design knowledge has been extracted, IDEF0 diagrams can be used to represent them, and it has been shown that they can be automatically generated. An additional benefit of utilising IDEF0 diagrams is that they are widely used in industry. By providing the design knowledge, stored in the IDEF0 diagrams, to subsequent users carrying out specific design tasks, it can be used to aid them in creating more efficient designs, more quickly.

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